Shear Behaviour of Steel-Fibre-Reinforced Concrete Beams

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SHEAR BEHAVIOUR OF STEEL-FIBRE-REINFORCED CONCRETE BEAMS

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ABSTRACT
The present work sets out to investigate the potential advantages of adding steel fibres to the concrete mix in order to enhance the structural response of concrete structures. In particular, the shear behaviour of steel-fibre-reinforced concrete (SFRC) beams was studied using Non-linear Finite-Element Analysis (NLFEA). The work aimed at assessing the potential of using steel fibres to reduce the amount of conventional steel reinforcement without compromising ductility and strength requirements set out in design codes. To achieve this, the spacing between shear links was increased while steel fibres were added to see whether or not the loss of shear strength can be compensated for in this way. This can speed construction as laying out shear links can be time consuming. It is also useful in situations where the amount of shear reinforcement required can lead to congestion of shear links.

Emphasis was initially focused on the analysis of available experimental data describing the effect of steel fibres on key material properties such as the tensile strength, pull-out behaviour and the stress-strain curve describing the behaviour of SFRC before and after cracking. Subsequently, a suitable constitutive model was selected which allowed for the salient features of SFRC behaviour namely: the fibre length, the ratio between its length and diameter, the fibre content (expressed as a volume fraction) as well as the bond strength between fibres and surrounding concrete. The material model was then implemented into a well known commercial NLFEA package (ABAQUS). The numerical model was carefully calibrated against existing experimental data to ensure the reliability of its predictions. Parametric studies were subsequently carried out. The study provided insight into how the steel fibres can help reduce the amount of conventional shear links.

INTRODUCTION

The work presented in this article aims to examine the shear behaviour of steel-fibre-reinforced concrete (SFRC) beams using Non-linear Finite-Element Analysis (NLFEA). The effect of the steel fibres is directly modelled into the existing concrete material model employed by ABAQUS (2007) to describe its nonlinear behaviour. This is achieved by appropriately modifying the stress-strain relationship of concrete in uniaxial tension. The resulting model was calibrated using existing experimental data on shear response of SFRC beams with fibre volume fraction (V_f) of 1% (Campione et al, 2006). The beams were initially designed with shear reinforcement less than that required so as to cause shear failure (so in one arrangement some shear links were provided while no links were provided in the other case). Subsequently, a parametric study was carried out using NLFEA to examine both arrangements but with the full practical range of fibre dosages considered. Conclusions were thus made on the potential for fibres to compensate for reduction is shear links.

METHODOLOGY

Constitutive Models for SFRC

Based on the available published test data, the introduction of steel-fibres into the concrete mix predominantly results in an increase in tensile and flexural strengths (Cho and Kim, 2003; Tlemat et al, 2006). It is important to point out that there is considerable scatter that characterizes the available test data. Apart from the obvious parameters that affect the strength of plain concrete (i.e. the water/cement ratio), the exhibited scatter can be also attributed to a wide range of parameters linked to the steel fibre used (i.e. the fibre length, the aspect ratio between the length and the diameter of the fibre, the volume fraction of the fibres as well as their shape, end arrangement – e.g. hooked or straight – and strength). This has led to the development of different material models to describe the behaviour of SFRC in tension, e.g. the models proposed by RILEM TC 162-TDF (2000; 2003); Barros and Figueiras (2001) and Tlemat et al (2006); Lok and Pei (1998); Lok and Xiao (1999). A calibration study was undertaken by Abbas et al (2010; 2010), which concluded that the model proposed by Lok and Xiao (1999) is the most suitable one to be adopted for the present study.

ABAQUS Models for SFRC

The material model adopted by ABAQUS to describe concrete behaviour is the “brittle cracking model”, which is available in ABAQUS/Explicit (2007). This model is designed for cases in which the material behaviour is dominated by tensile cracking as is normally the case for structural concrete. Thus the uniaxial stress-strain relation in compression is simply assumed to be linear elastic throughout the loading history. The behaviour of concrete in tension (prior to cracking) is assumed to be linear elastic. The post-cracking phase is described using tension-stiffening, which allows the uniaxial stress-strain relation to be defined. A smeared crack approach is adopted to model the cracking process that concrete undergoes. For purposes of crack detection, a simple Rankine criterion is used to detect crack initiation (i.e. a crack forms when the maximum principal tensile stress exceeds the specified tensile strength of concrete). In the present study, the concrete medium is modelled by using a dense mesh of 8-node brick elements. 1D bar elements representing the steel reinforcement were placed to mimic the actual arrangement in the specimens modelled (e.g. cover allowed for ..etc). Steel constitutive behaviour follows a simple bilinear hardening model that follows Eurocode 2 (2004).

RESULTS AND DISCUSSION

The beams considered were investigated experimentally by Campione et al (2006). These were four-point tests (shear span to effective depth ratio of 2.8) on simply-supported beams with spans of 2500 mm, depth of 250 mm and width of 150 mm. Two beam configurations were tested, both with steel fibres with V_f = 1% and one beam with shear links while the other without any shear links. The beams were reinforced with two longitudinal bars of 20 mm diameter at the bottom and two 10 mm bars at the top. In one arrangement, shear links of 6 mm diameter were placed at a pitch of 200 mm, whilst no shear links were provided in the second case. The yield stress of steel for the longitudinal bars and shear links were 610 MPa and 510 MPa, respectively. The concrete compressive cylinder strength was 41.2 MPa. Steel fibres provided in both cases had hooked ends and length of 30 mm and diameter of 0.5 mm.

The experimental results were compared to their corresponding ABAQUS predictions and there was good correlation (see Figures 1a and 1b).

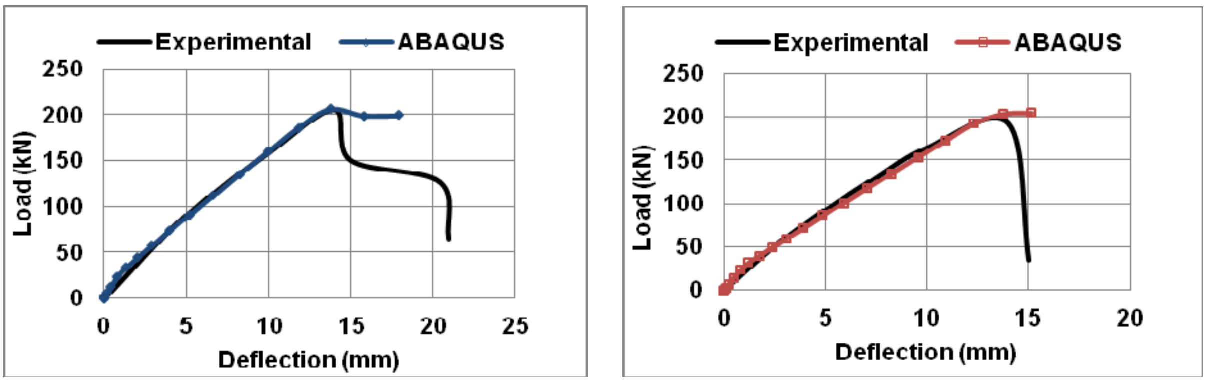

Figure 1: Comparison between experimental results and numerical predications for SFRC beams with Vf = 1% (a) with shear links and (b) without shear links

To examine the effect of different fibre dosages on the shear behaviour beyond the volume fractions studied experimentally, NLFEA for both beams were carried out with volume fractions: 0%, 1%, 1.5%, 2% and 2.5%. This range was adopted as it represents fibre dosages that can be used in practice as higher volume fractions than 2.5% can be difficult to mix properly with the concrete paste. The results of these studies are discussed next.

SFRC beams with shear links

Figure 2 contains the numerical results obtained for SFRC beams with various volume fractions and shear links (comprising 6 mm bar diameter at 200 mm spacing). The load-deflection curves show that the beam without fibres failed early at a deflection of 13.76 mm at a load bearing capacity of 189.9 kN. In contrast, there is a gradual increase in the peak strength and ductility as the fibres content is increased.

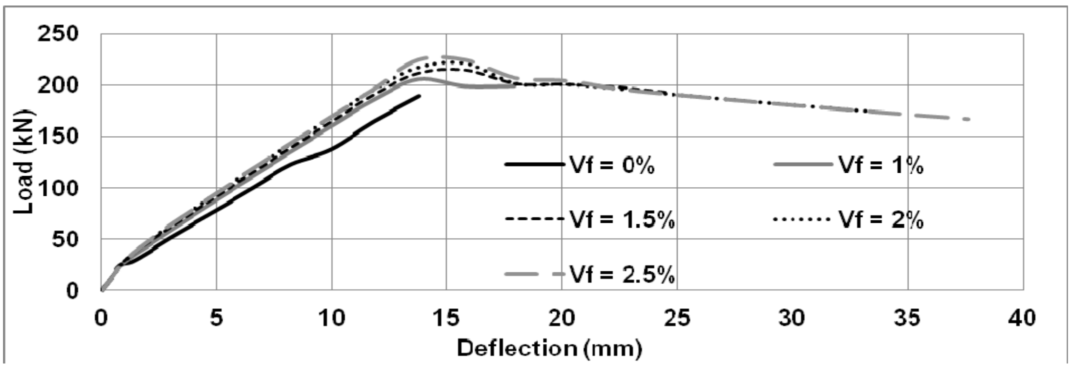

Figure 2: Load-deflection curves for SFRC beams with various fibre contents and shear links

To study this further, the key results have been summarised in Table 1 below (P_{max} represents the maximum strength, P_u the ultimate (i.e. residual) strength, δy the yield deflection, δu the ultimate deflection and μ the ductility.

V_f (%)	P_{max} (kN)	P_{max}/ P_{maxo}*	P_u (kN)	P_u/ P_{max}†	δy (mm)	δu (mm)	μ=δu/δy‡
0%	189.9	1.00	189.9	1.00	13.76	13.76	1.00
1%	207	1.09	199.14	0.96	13.76	17.97	1.31
1.5%	215.5	1.13	192.36	0.89	13.76	24.73	1.80
2%	220.5	1.16	173.72	0.79	13.76	33.64	2.44
2.5%	228.5	1.20	167.14	0.73	13.76	37.65	2.74

Table 1: Results for SFRC beams with shear links (* this ratio represents the change in maximum strength, † this ratio represents the change in residual strength, ‡ this ratio represents the change in ductility)

The Table results show that the peak strength has increased by about 10% by adding fibres with V_f = 1% and up to 20% with V_f = 2.5%. The stiffness has also increased noticeably in comparison to the case without fibres. This suggests that there are clear benefits of adding fibres at the serviceability limit state.

Furthermore, the ductility has also increased significantly by about 31% by adding fibres with V_f = 1% and up to 174% with V_f = 2.5%. This demonstrates the potential for fibres to provide a ductile mode of failure, which is useful for ultimate limit-state considerations (albeit with a reduced residual strength accounting for 96% of the maximum strength with V_f = 1% and 73% with V_f = 2.5%). This “softening” trend in the present case should not be interpreted to conclude that increasing fibre content will reduce the residual strength. It is simply that the ultimate deflection is higher for these high fibre contents and the residual load is determined at that deflection point (so for the beam without fibres the ultimate strength and residual strength are equal simply because the failure mode is brittle and there is no ductility). Therefore, the residual strength can always be taken at a shorter displacement to suit a prescribed ductility demand. Thus to utilise the large increase in ductility, consideration should be given to the resulting residual strength (although in the present case, 73% of the maximum strength can still be retained at a very high ductility ratio of 173%).

SFRC beams without shear links

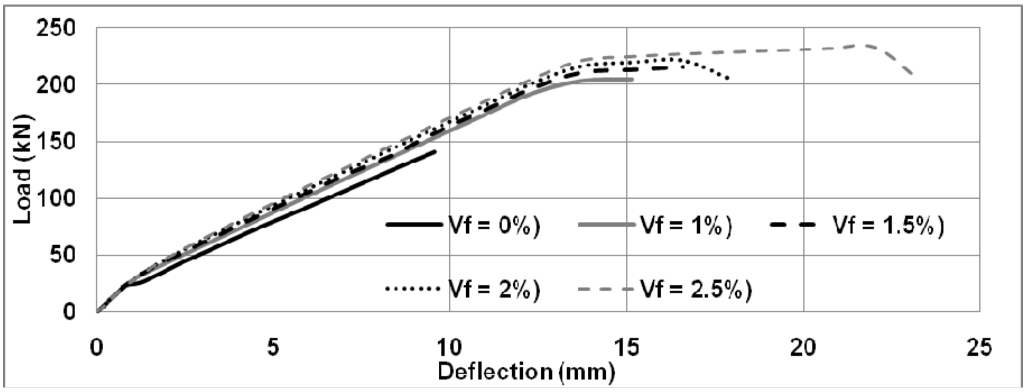

Figure 3: Load-deflection curves for SFRC beams with various fibre contents but without shear links

A further study was carried out by removing all the shear links, then increased amounts of steel fibres were added and analysed using ABAQUS. The results are presented in Figure 3 and are summarised in Table 2.

V_f (%)	P_{max} (kN)	P_{max}/ P_{maxo}*	P_u (kN)	P_u/ P_{max}†	δy (mm)	δu (mm)	μ=δu/δy‡
0%	141.1	1.00	141.1	1.00	9.56	9.56	1.00
1%	204.6	1.45	204.6	1.45	13.72	15.15	1.11
1.5%	216	1.53	216	1.53	13.72	16.58	1.21
2%	222	1.57	203. 6	1.45	13.72	18	1.31
2.5%	235	1.67	204.9	1.45	13.72	23.26	1.70

Table 2: Results for SFRC beams without shear links (symbols as in Table 1)

The results show that the peak strength has increased by about 45% by adding fibres with V_f = 1% and up to 67% with V_f = 2.5%. These increases are more than double the increases in the case when shear links were provided. This reflects the extremely brittle nature of the beams without shear links and demonstrates the potential for fibres to enhance both peak strength and ductility (the increases for the latter are 11% for V_f =1% and 70% for V_f = 2.5%, which are lower than when links were provided confirming the brittle nature of this case and potential for fibres to address that).

Comparisons between SFRC beams with and without shear links

Figures 4a-e depicts a comparison between the load-deflection responses for beams with and without shear links. Figure 4f represents a comparison between the energy absorption in the two cases, which also gives an indication of ductility and strength.

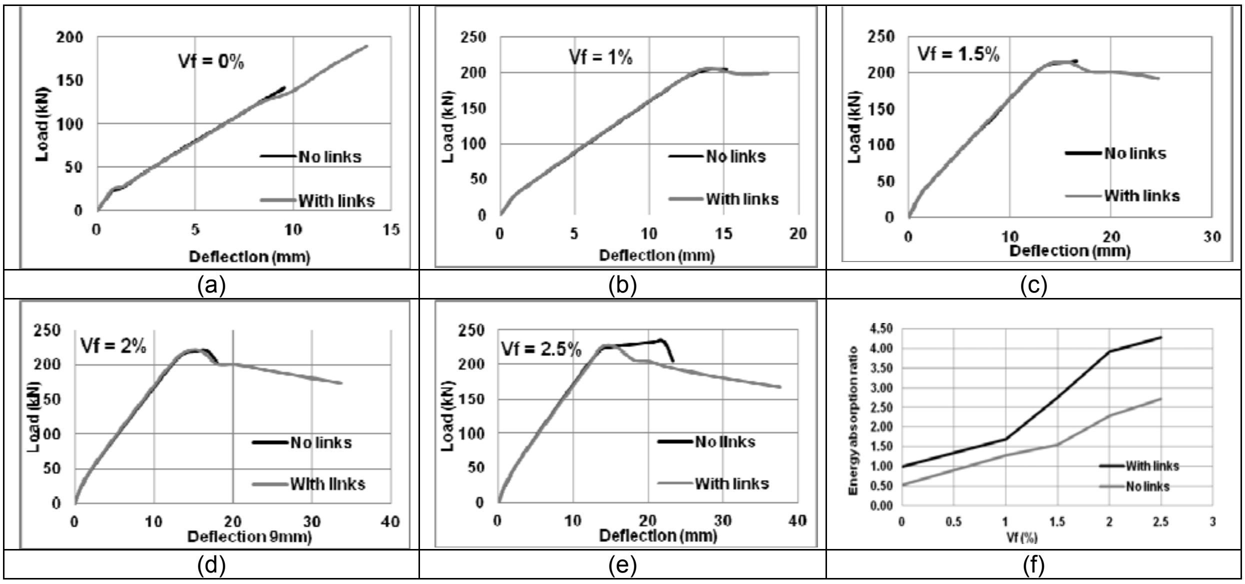

Figure 4: Comparison between SFRC beams with and without links (a-e) load-deflection curves and (b) energy absorption ratios

Considering these results, conclusions could be made on the potential for fibres to replace shear links once the latter are removed. From Figure 4a, it can be seen that in the absence of fibres when all shear reinforcement is removed, the load carrying capacity and deflection at failure dropped by 26% and 31%, respectively. This is expected as the beam in the absence of both fibres and links will fail in a brittle manner. From Figures 4b-e, it is interesting to see that the trend is the same up to the peak load, with the combination of fibres and links leading to increased ductility beyond the peak load. In terms of energy absorption, the addition of fibres increases it by about 160% without links and up to 325% with links.

CONCLUSIONS

A comparison between the SFRC beams with and without shear links demonstrates that steel fibres have the potential to enhance the shear capacity and ductility. This demonstrates that the fibres have the potential to compensate for a reduction in shear links. This can be useful in situations where the amount of shear reinforcement required can lead to congestion of the links and can also simply complex construction arrangements.

In the present case, the enhancement is larger when both fibres and links are provided. However, it must be stressed that in the current study, the beams were initially provided with shear reinforcement less than that required so as to cause shear failure. In practice, the shear reinforcement provided will be much higher. An extension to the present work currently being undertaken by the authors has indicated that the combination of fibres and shear links beyond a certain threshold can actually lead to reduced ductility (this is similar to the well-established over-reinforced behaviour observed in conventional reinforced-concrete beams).

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